Analyzing Simulated Very High Energy Gamma-ray data from Dark Matter Annihilation

Summer 2024 REU Final Presentation - Alex Sidler

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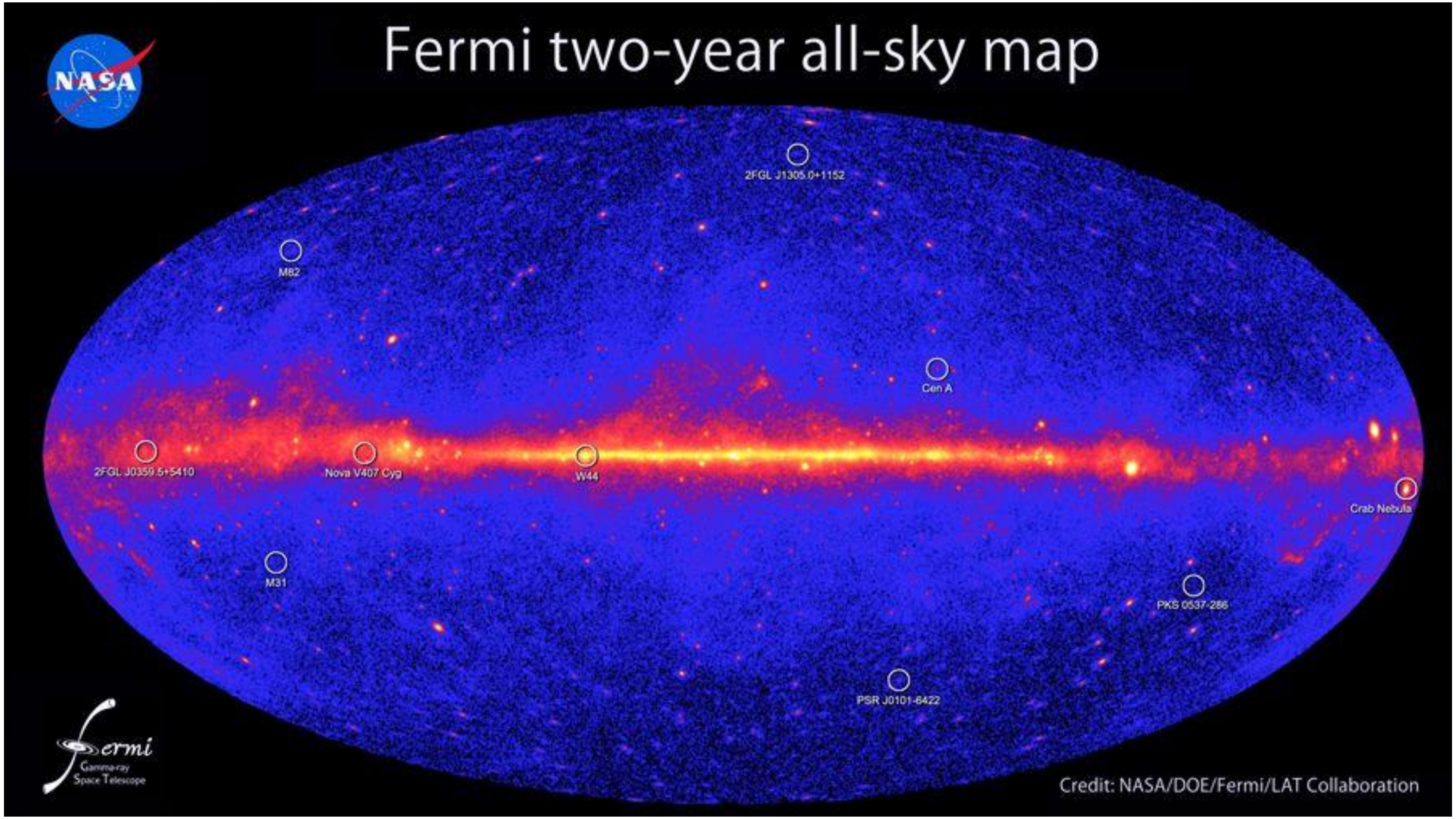
A **Python** package for **gamma-ray** astronomy

NEVIS LABORATORIES
COLUMBIA UNIVERSITY

NSF

Summary



1. Dark Matter

Evidence

WIMPs

2. Gamma-ray detection

CTAO

3. Analytical Methods

Background Estimation

Statistics

4. Results

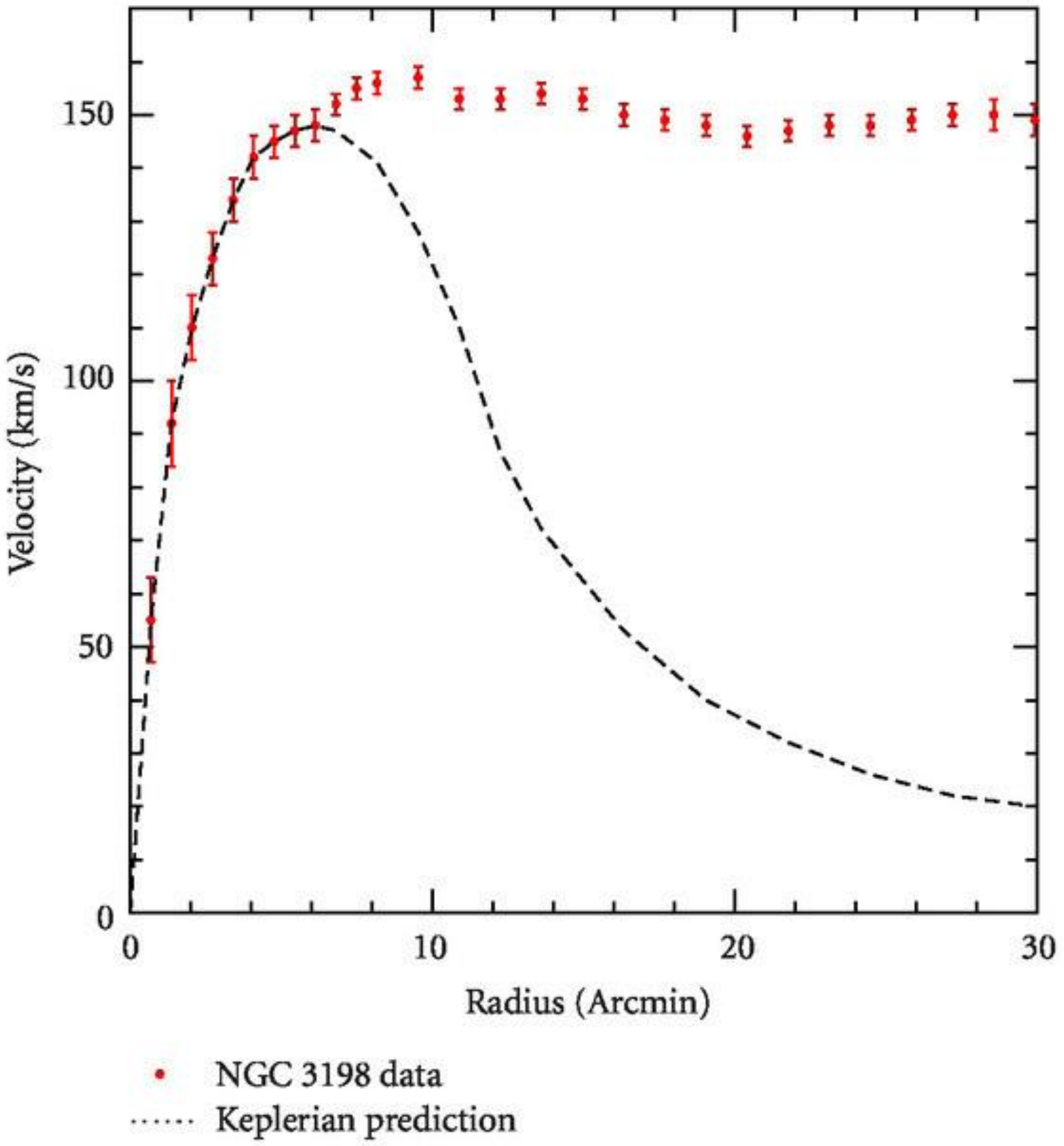


Figure courtesy of K. Garrett and G. Duda

Dark Matter

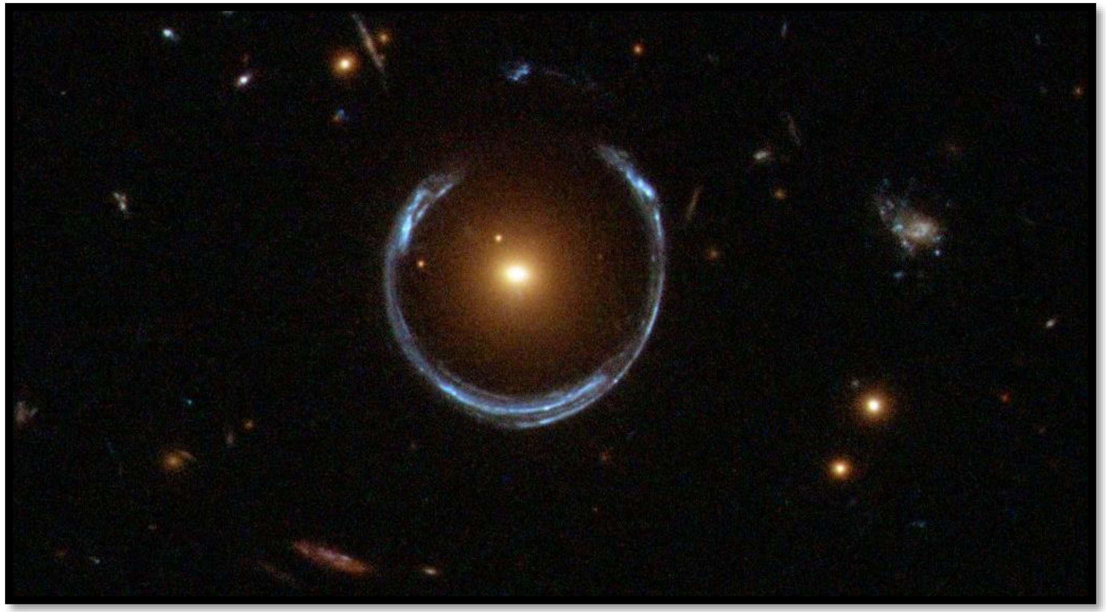
Evidence:

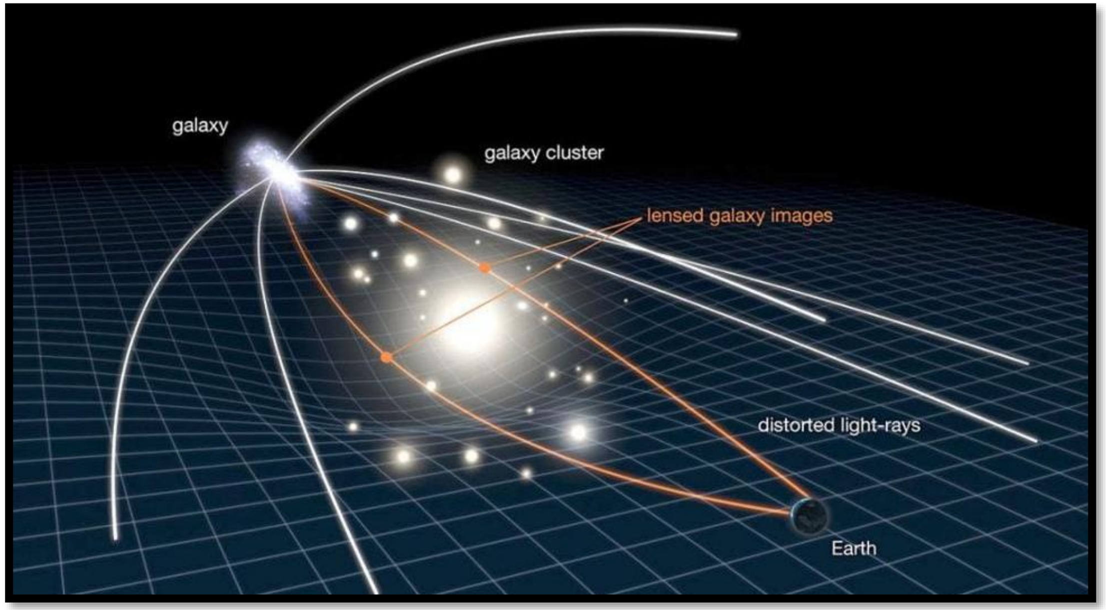
- Rotational curves of galaxies
- Outer mass should escape gravitational pull
- DM binding

Dark Matter (cont.)

More evidence:

Gravitational Lensing

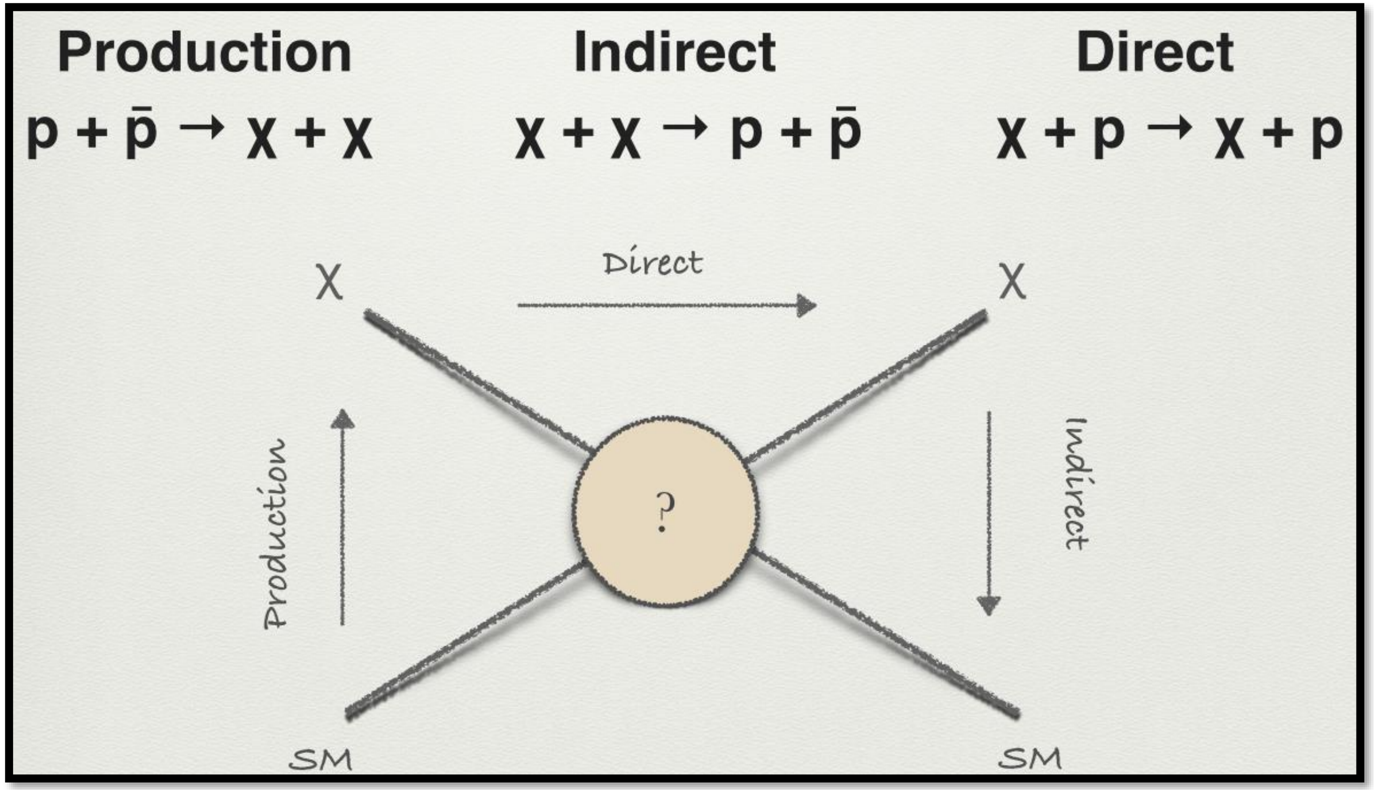




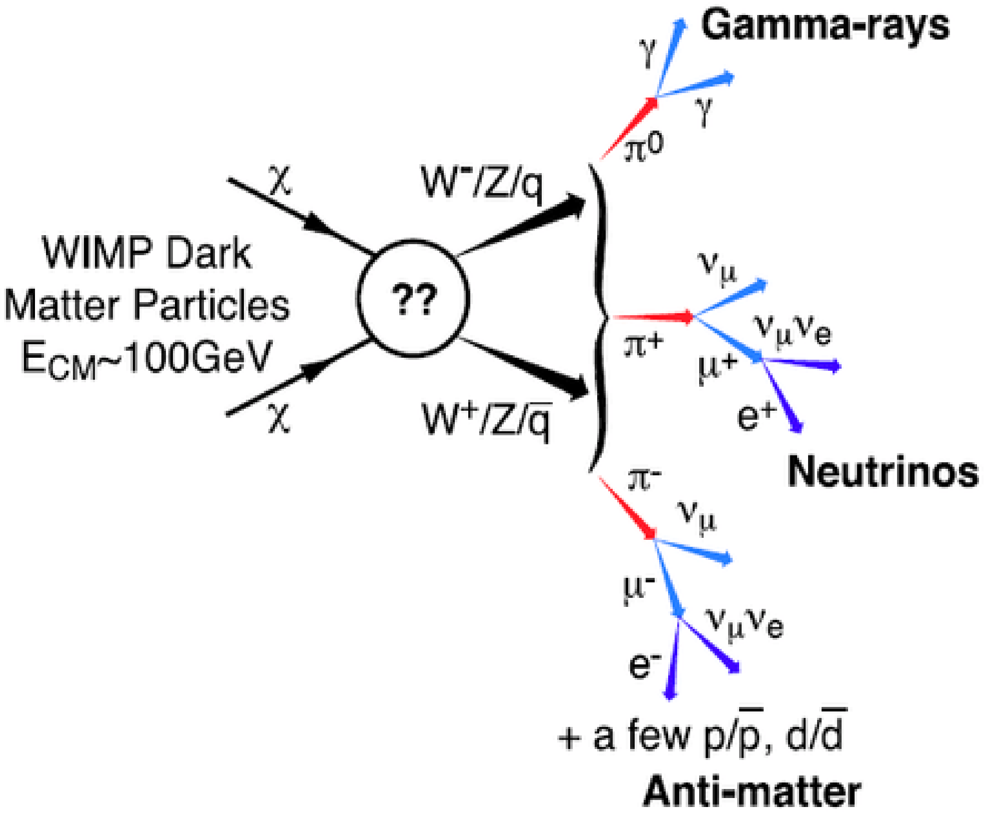
Why gamma-ray searches?

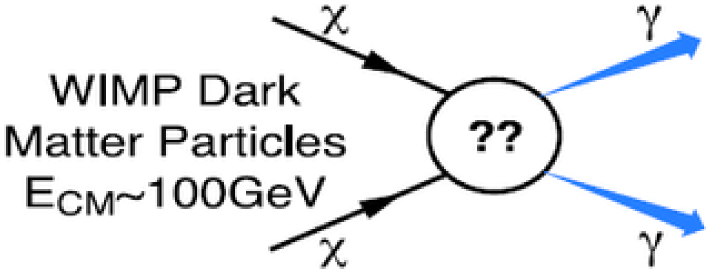
DM annihilation & decay

- We can analyze the resulting gamma rays!



WIMPs





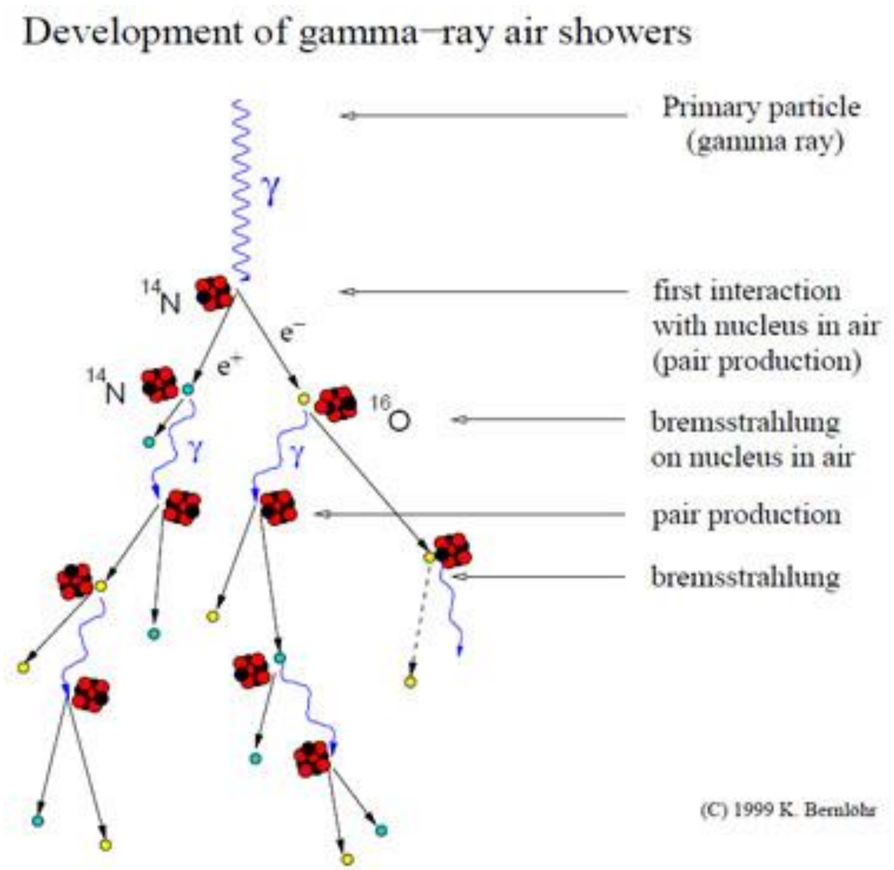
Weakly Interacting Massive Particles

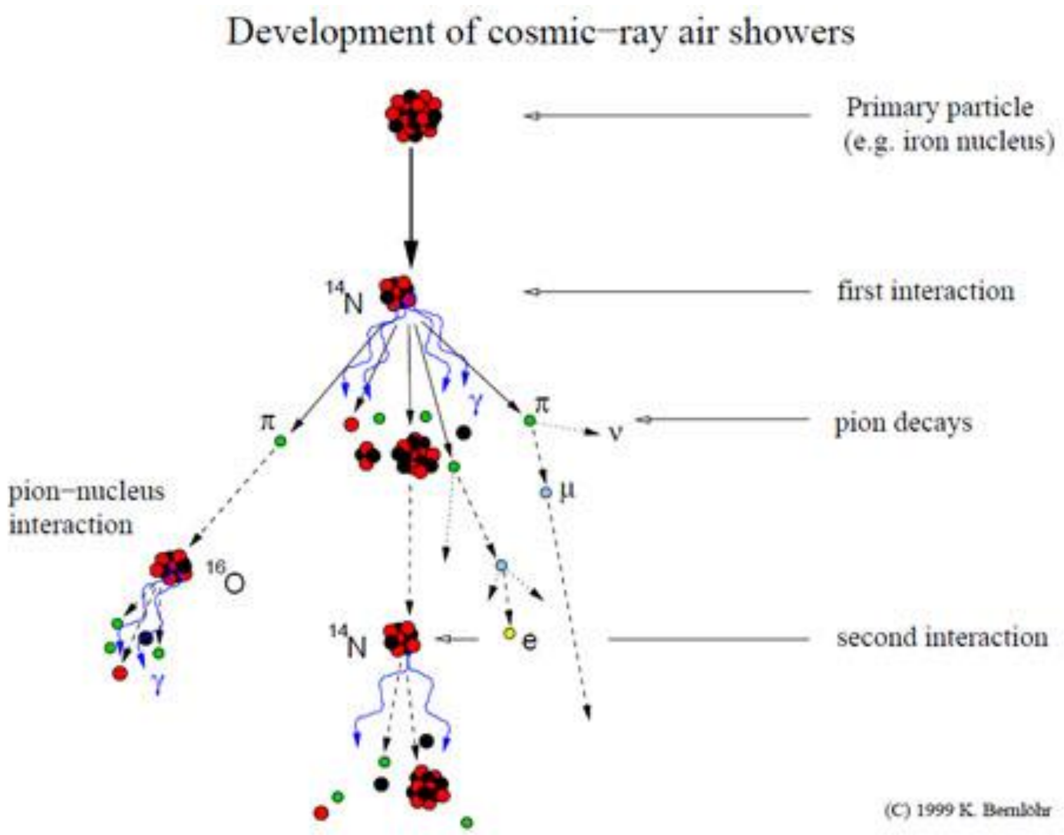
- "Cold" dark matter
- WIMP's theoretical mass determines energy of emitted gamma rays
- *Prompt emissions*
- *Secondary emissions*
- Mass range of 50GeV – 10TeV well motivated SUSY extensions of SM

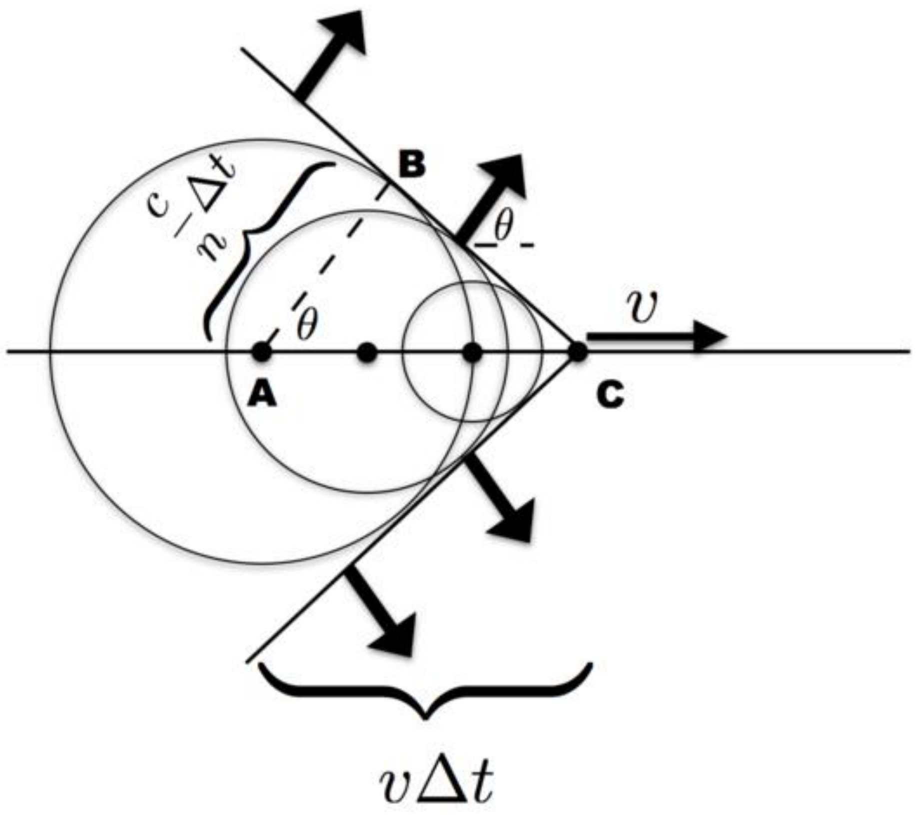
Air showers

Gamma rays travel through galactic & intergalactic space until they hit Earth

Interact with atmosphere (Bremsstrahlung)







Cherenkov Radiation

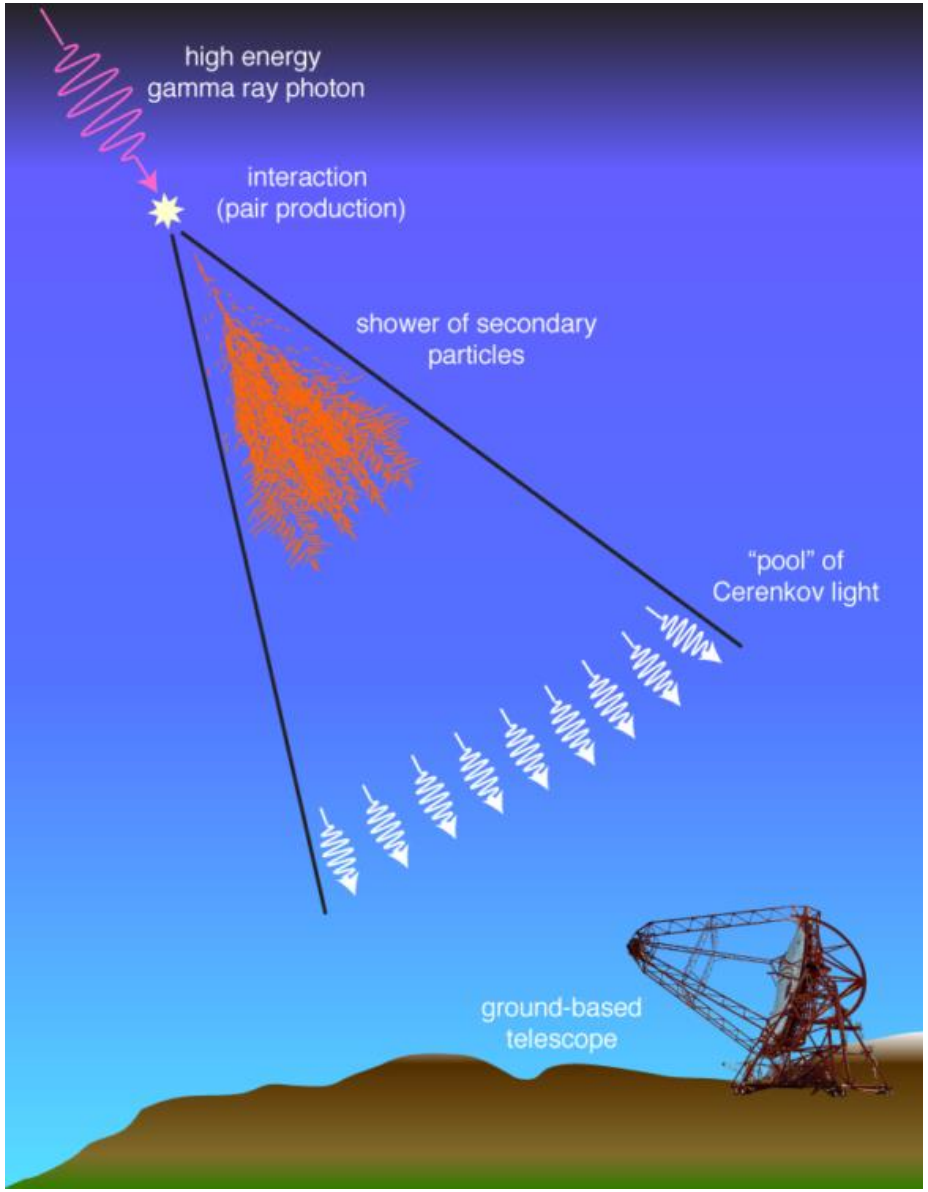
- Charged particles traveling faster than light (in medium)
- Emit light wavefront at a characteristic angle
- $cos\theta = \frac{v_p}{nc}$

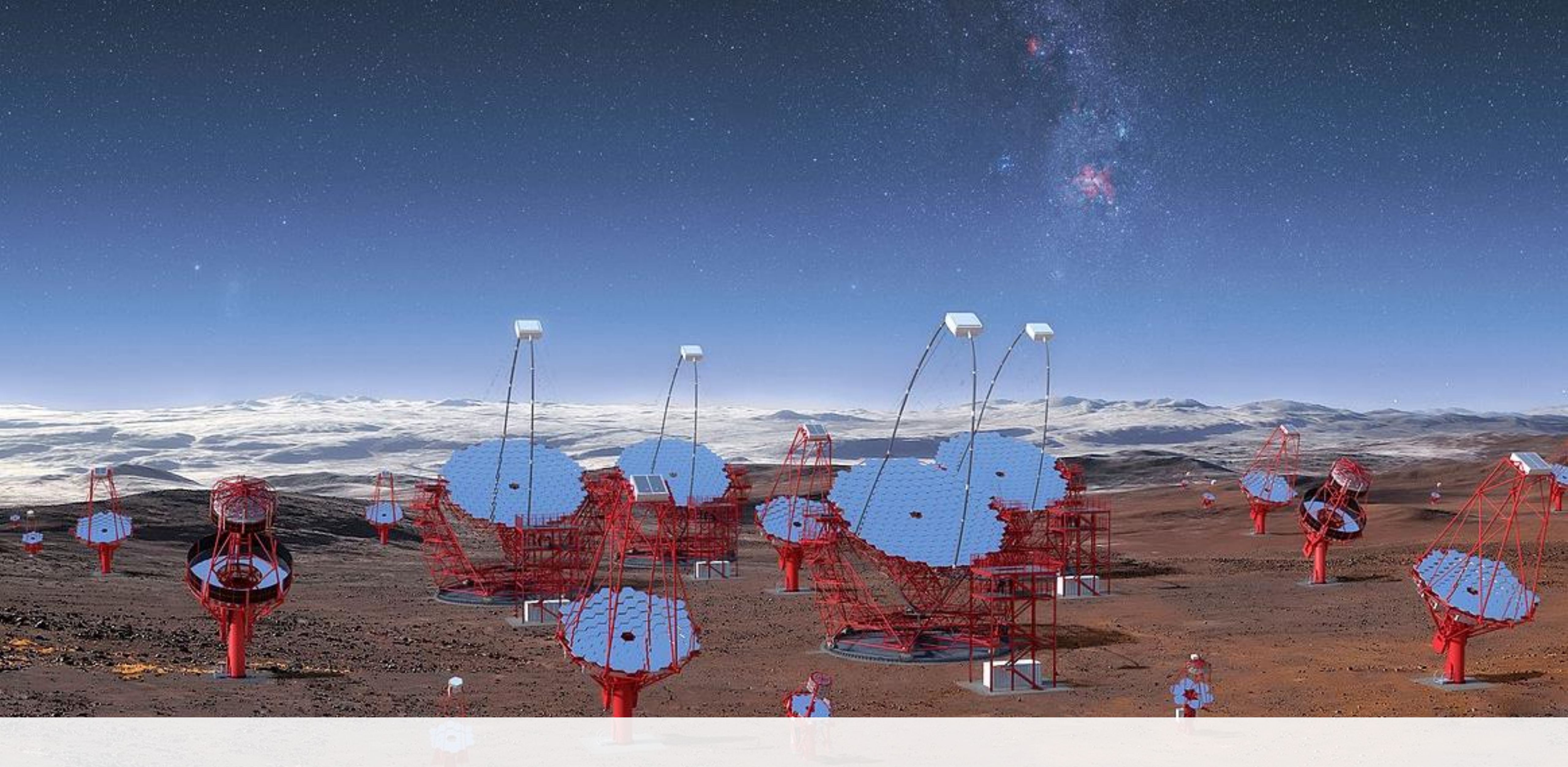
- Visible blue light is emitted
- Analogous to supersonic “boom” of sound wave

IACTs

Imaging Atmospheric Cherenkov Telescopes (IACTs)

- VERITAS
- CTAO





CTAO

CTAO - Performance

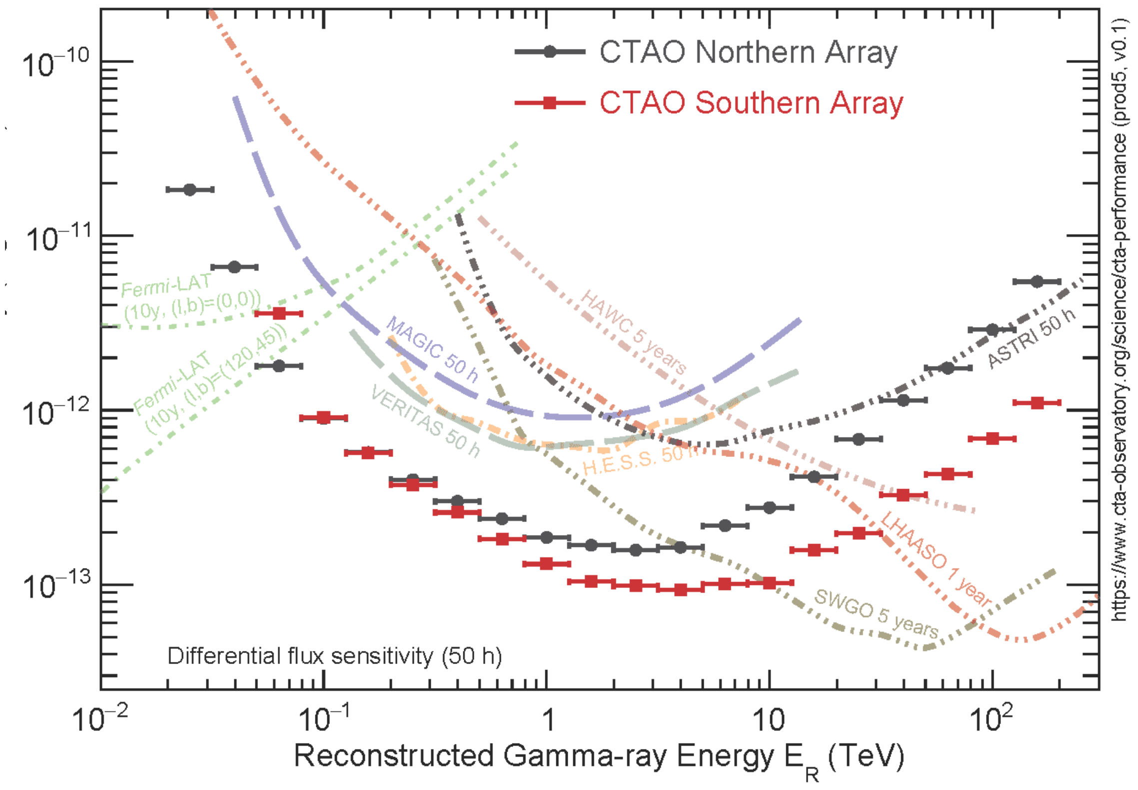


Figure courtesy of CTAO - Performance

- Unparalleled sensitivity in the 0.1 – 10 TeV range
- Wide range of observable energies 0.02 to 300 TeV
- Full sky coverage
- Open to a wide community

Gammapy & the second Science Data Challenge (SDC)

A **Python** package for **gamma-ray** astronomy

Gammapy:

- Gamma ray analysis package for python
- Open-source
- Community-developed

CTAO SDC:

- Simulated datasets for a variety of sources
- Goal: to demonstrate CTAO performance

Sources

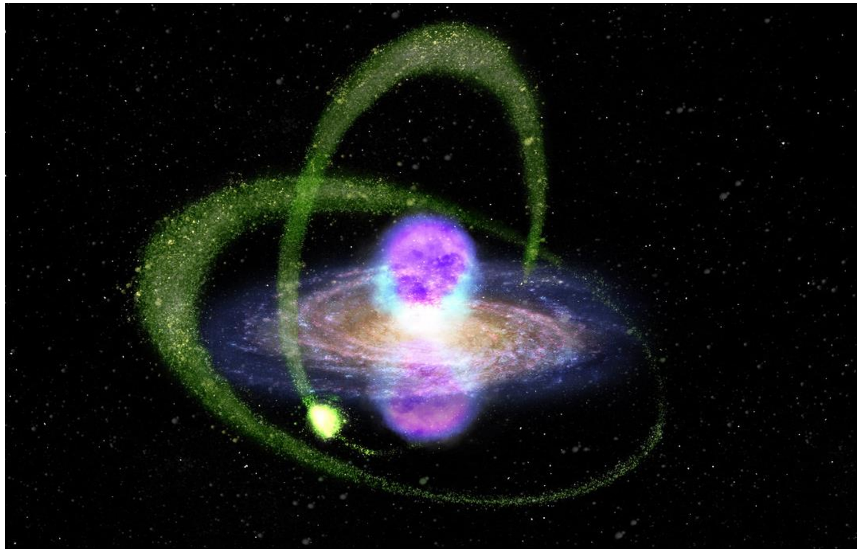
Willman-I

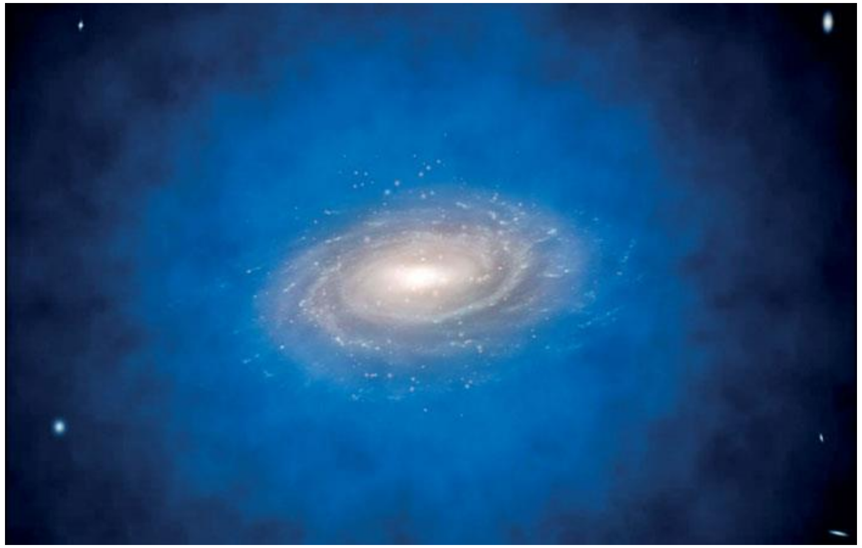
- Dwarf spheroidal galaxy

Sagittarius-II

- Dwarf spheroidal galaxy

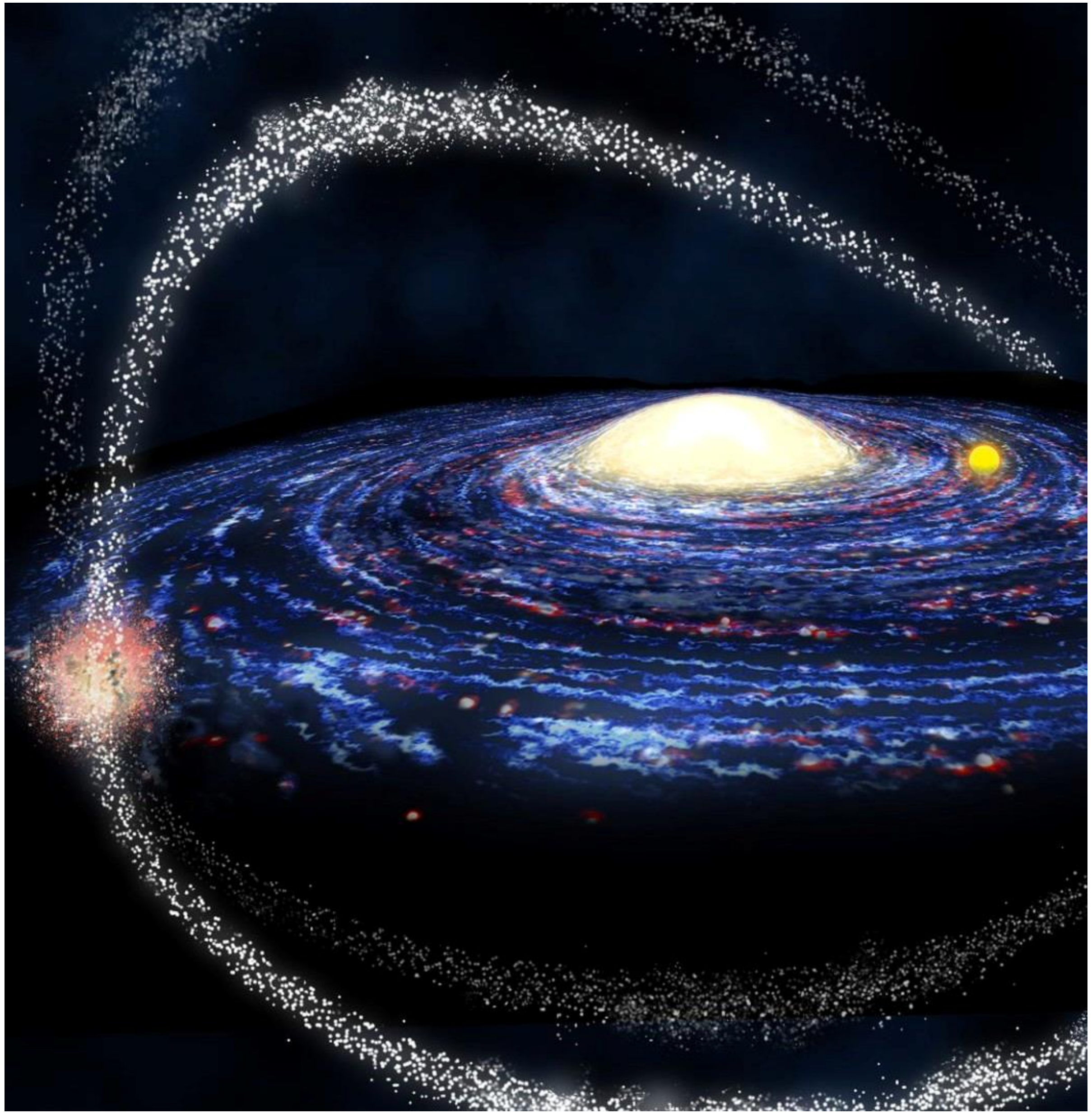
Galactic DM Subhalo

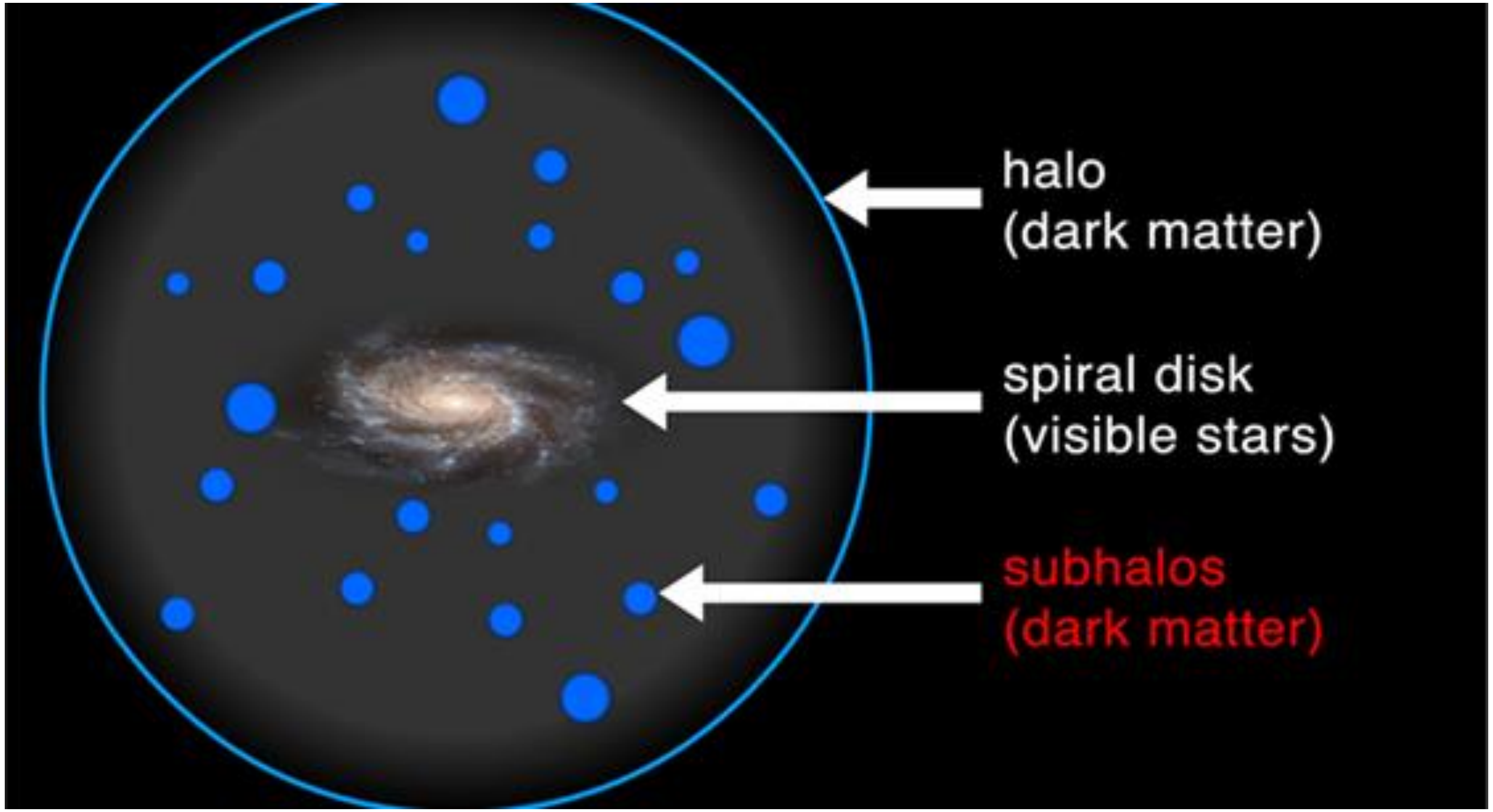




Dwarf Spheroidal Galaxies

- Good nearby DM targets
  - Large mass / luminosity ratio ($10 - 100 \, {}^{M_\odot}/_{L_\odot}$)
  - Expect no gamma –ray background
  - DM distribution unknown





DM Subhalos

Good nearby DM targets

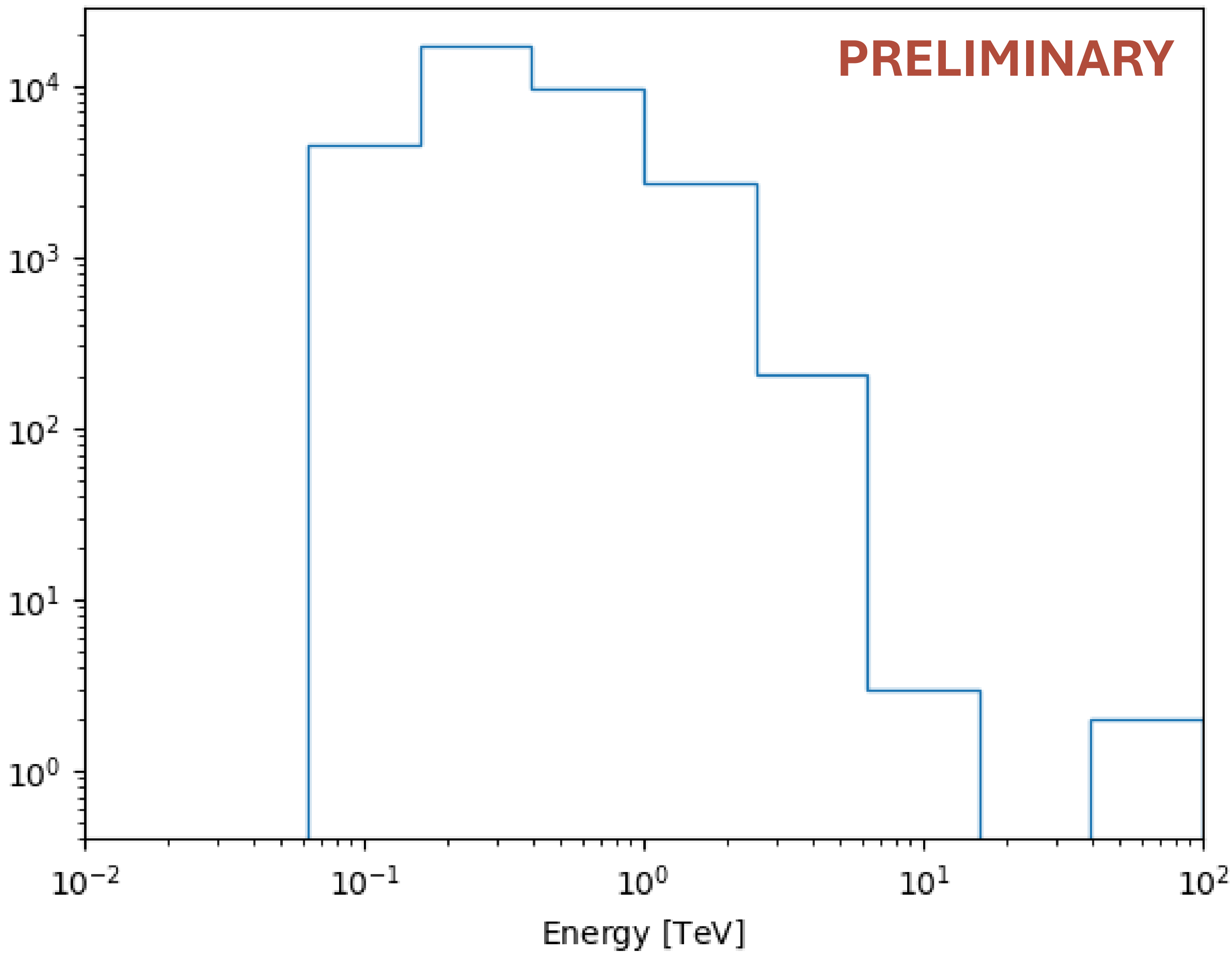
- Expect no gamma-ray background
- Galactic sources
- Can be very DM-dense
- Detected through gravitational lensing
- Hard to detect
- Not much info

Analysis Pipeline

- Background estimation
- Modeling, fitting, and more estimation

Markarian-421 validation source

Start: Counts



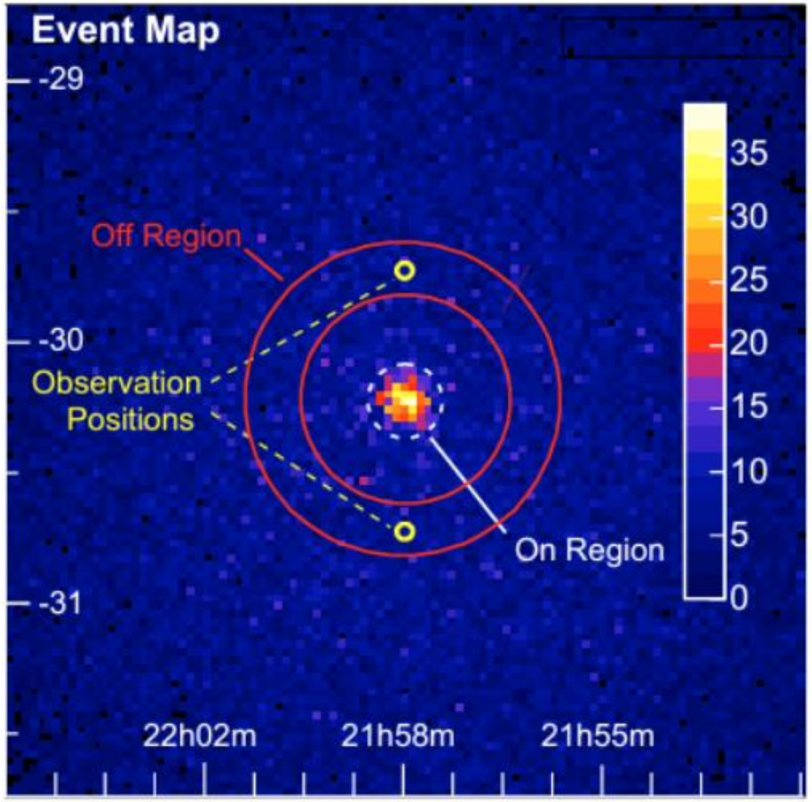
Background Estimation

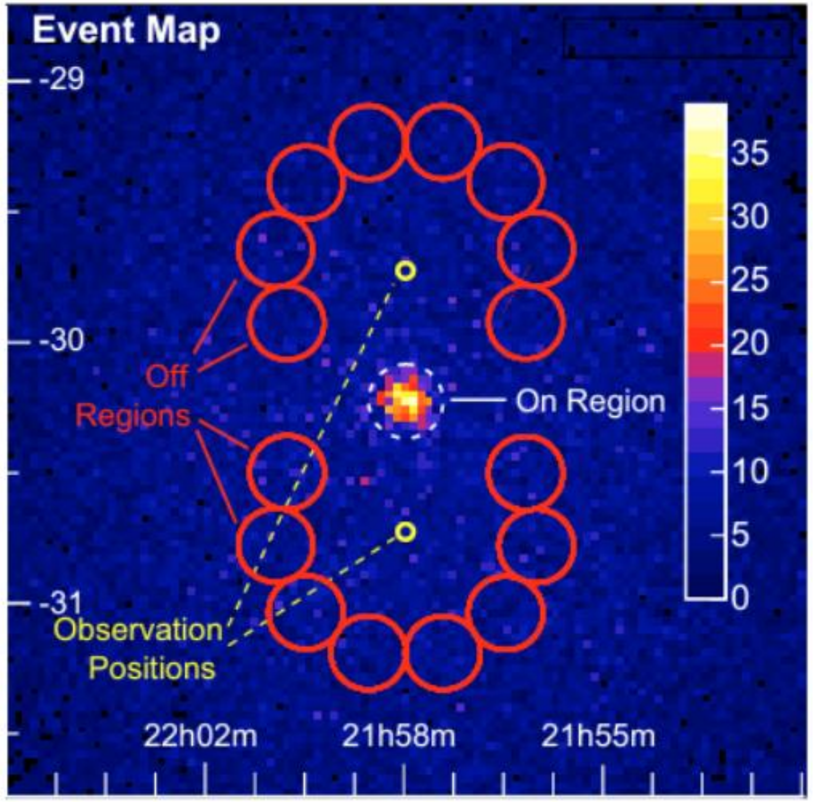
ON/OFF regions

Ring

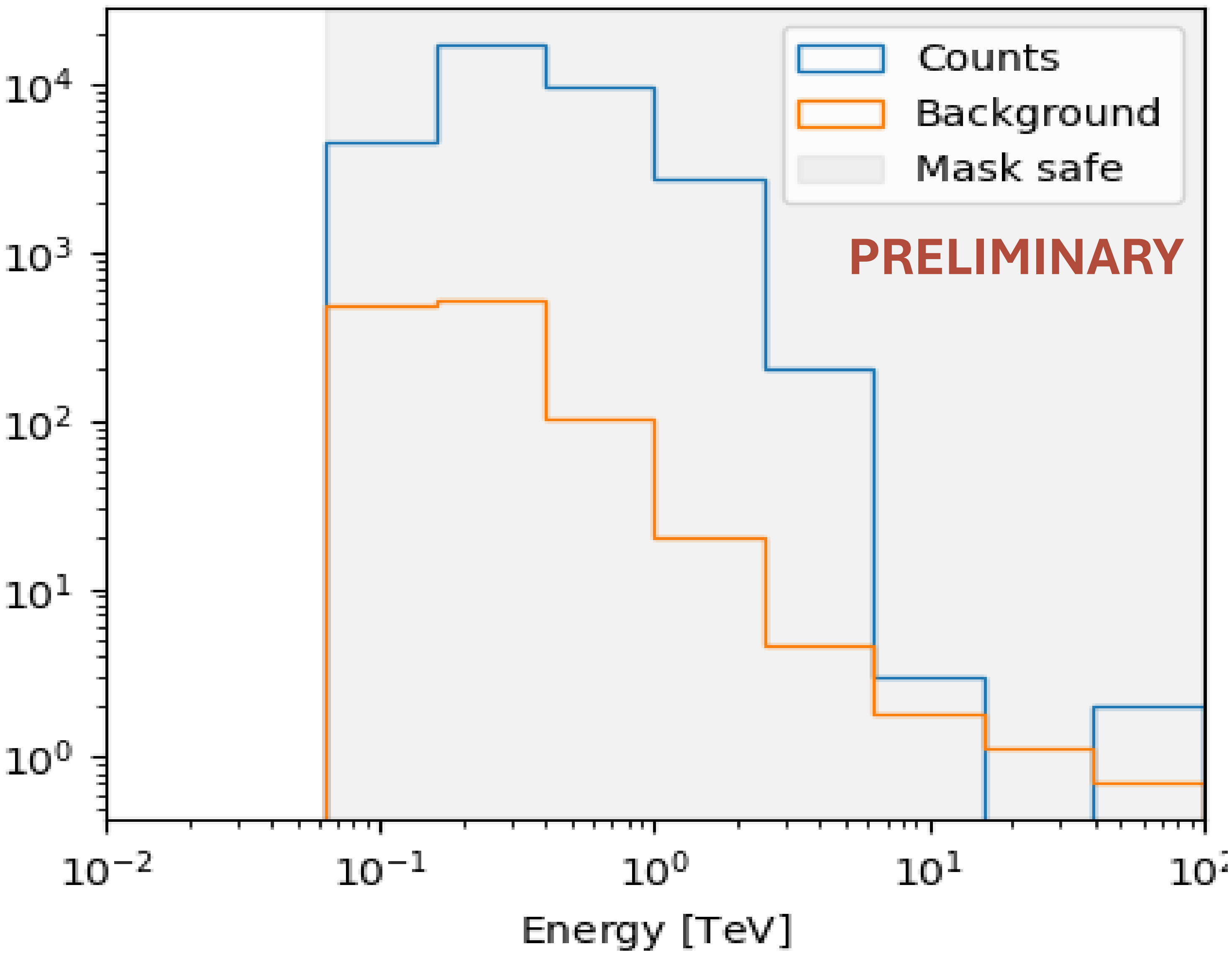
Reflected Regions

Estimate point source (exclusion region $\approx 0.07\ deg$)





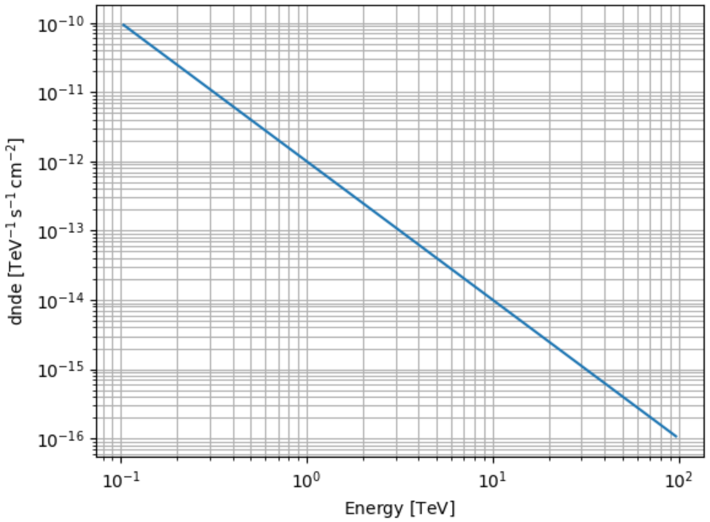
Excess



Counts
Background
Mask safe
PRELIMINARY
10^4
10^3
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
10^1
Energy [TeV]

Flux & Significance Estimation

$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{\Gamma}$$



Flux:

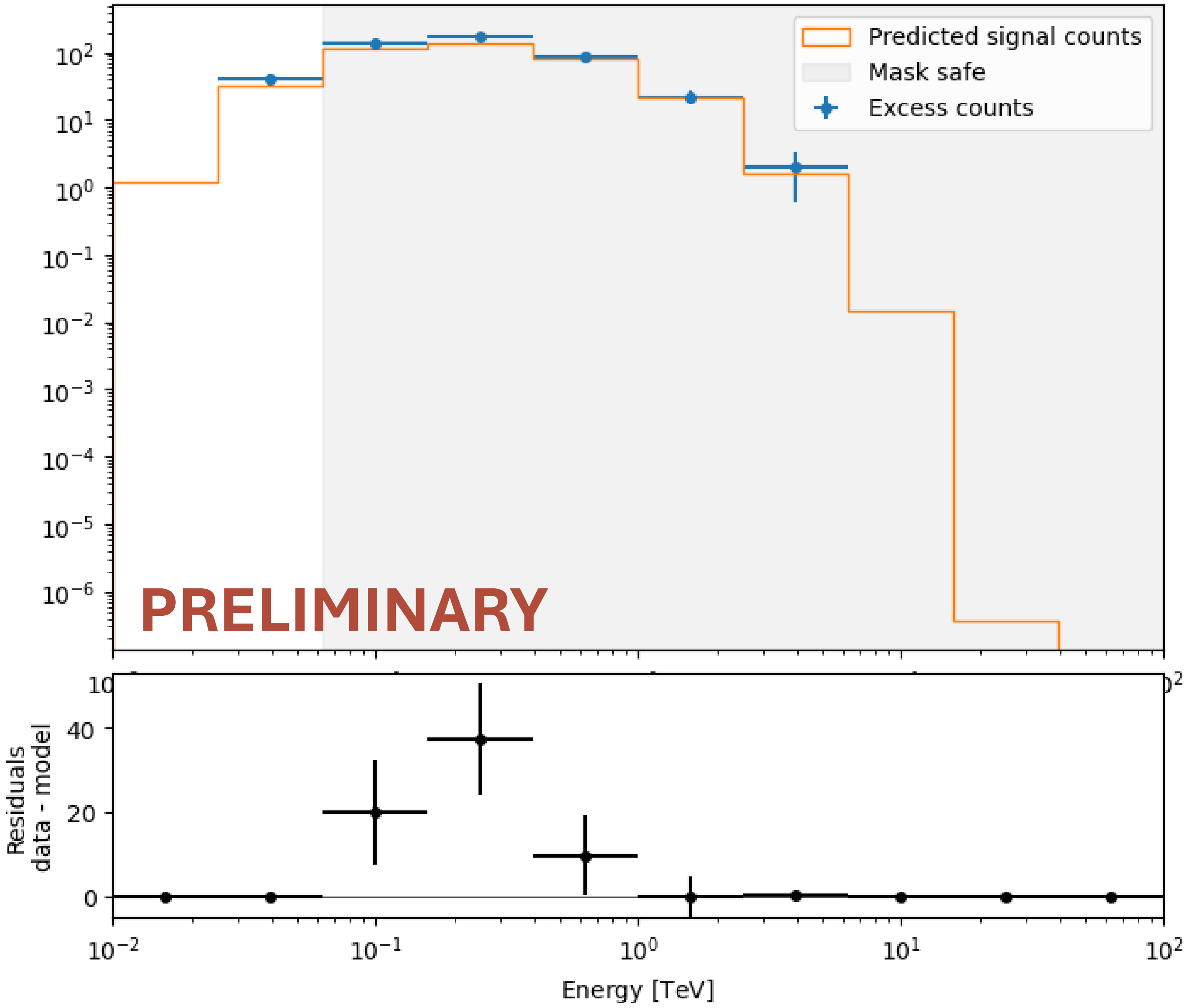
- TeV / (s cm2)

Estimation:

- Use a basic model (power law)
- Fit model to excess (minuit) & find χ^2
- Forward-folding algorithm for flux estimation (model-dependent)
- Backward-folding algorithm for significance map (not model-dependent)

Further analysis needed to account for trial factor (LEE)

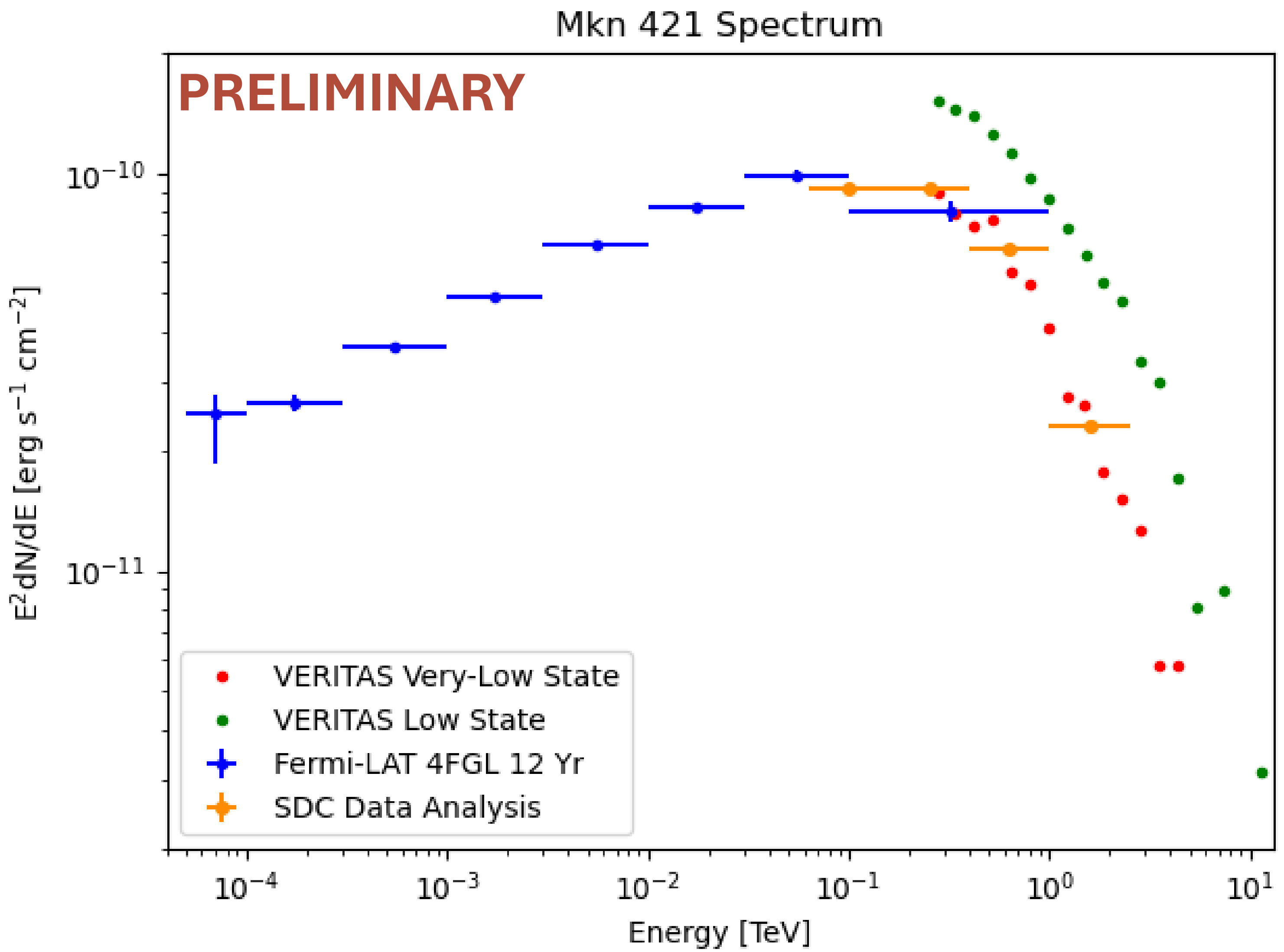
Residuals



Predicted signal counts
Mask safe
Excess counts
PRELIMINARY
Residuals
data - model
Energy [TeV]

Results!

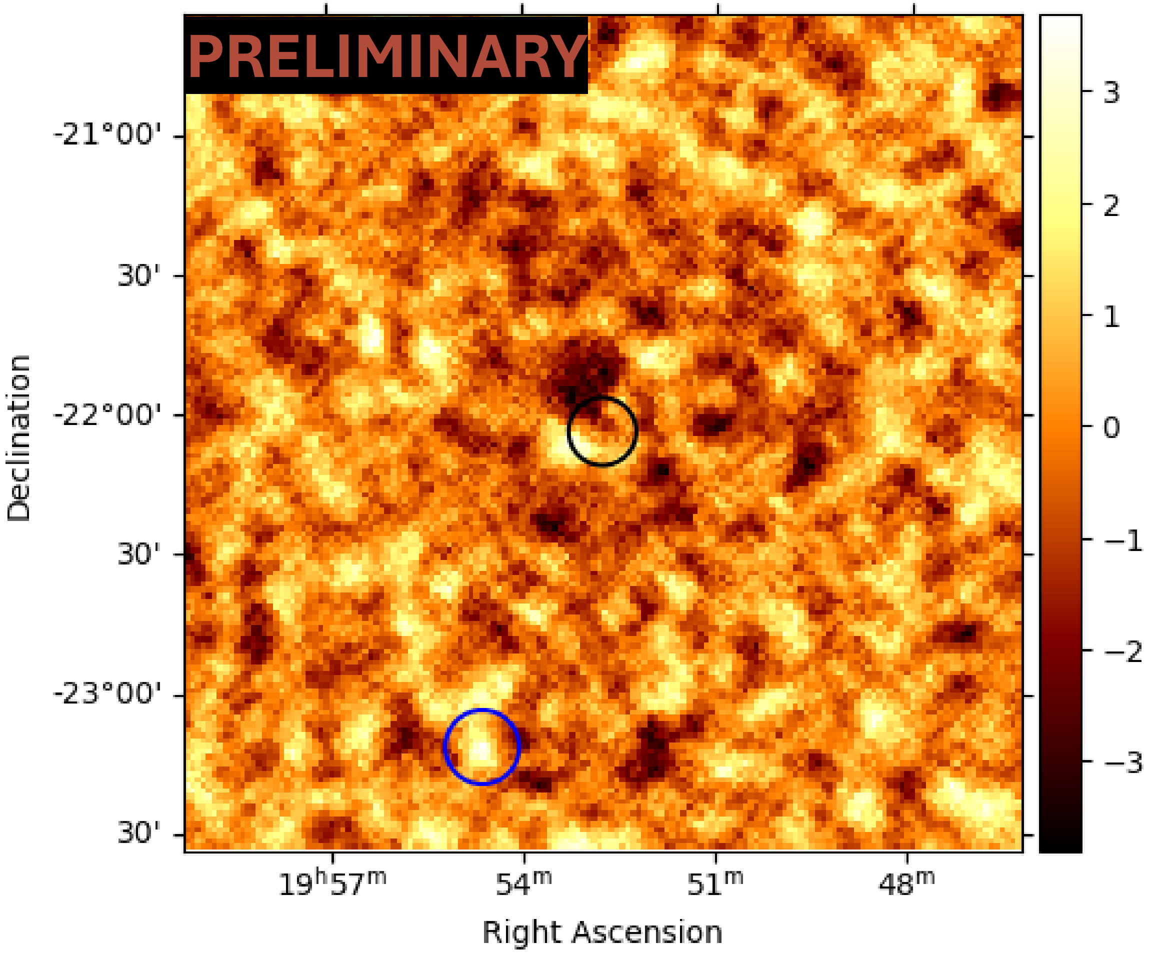
We got ‘em

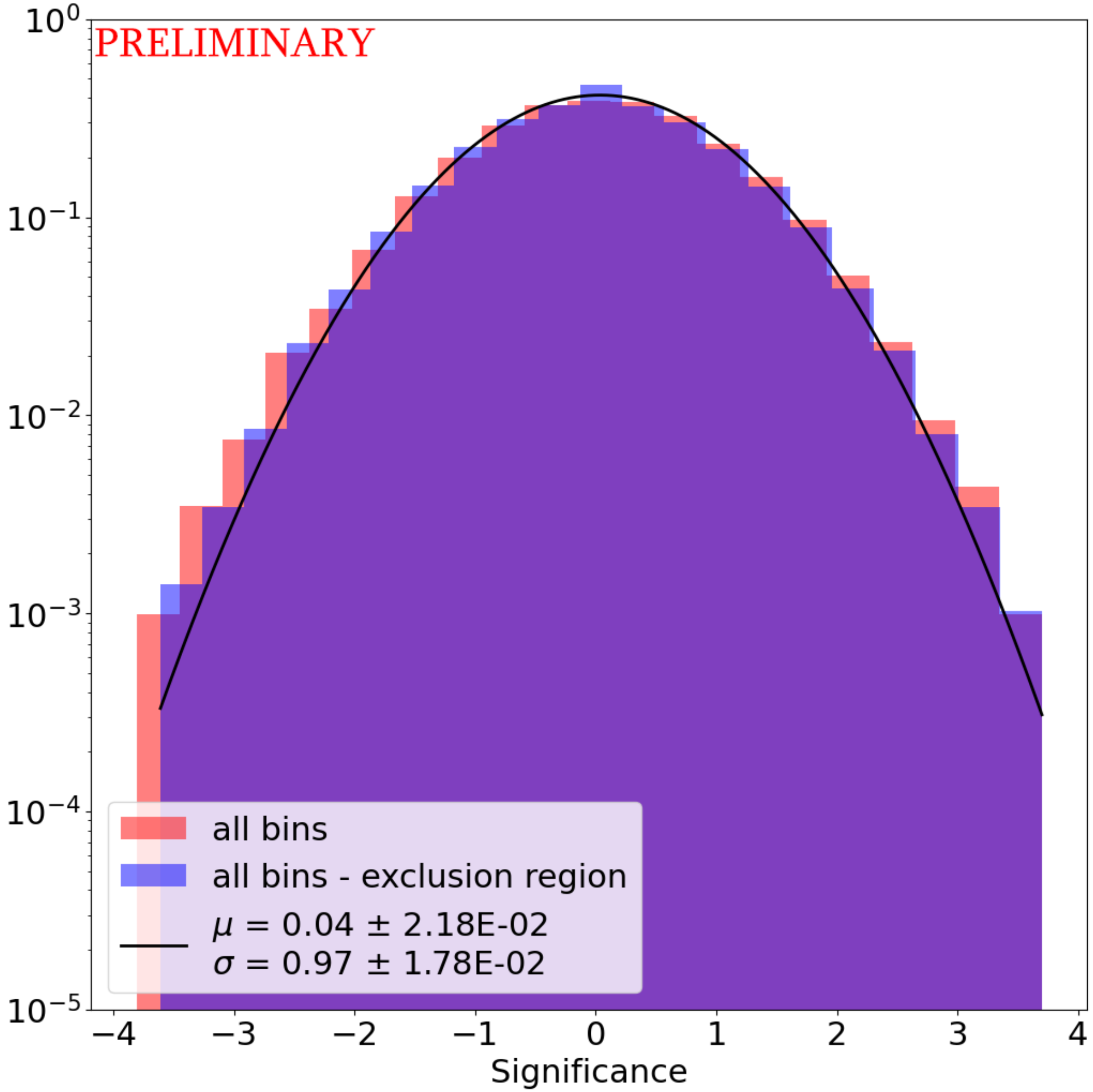


Markarian-421 Spectrum Comparison

Data from VERITAS & Fermi-LAT, Figure courtesy of Zach Curtis-Ginsburg

Sagittarius-2



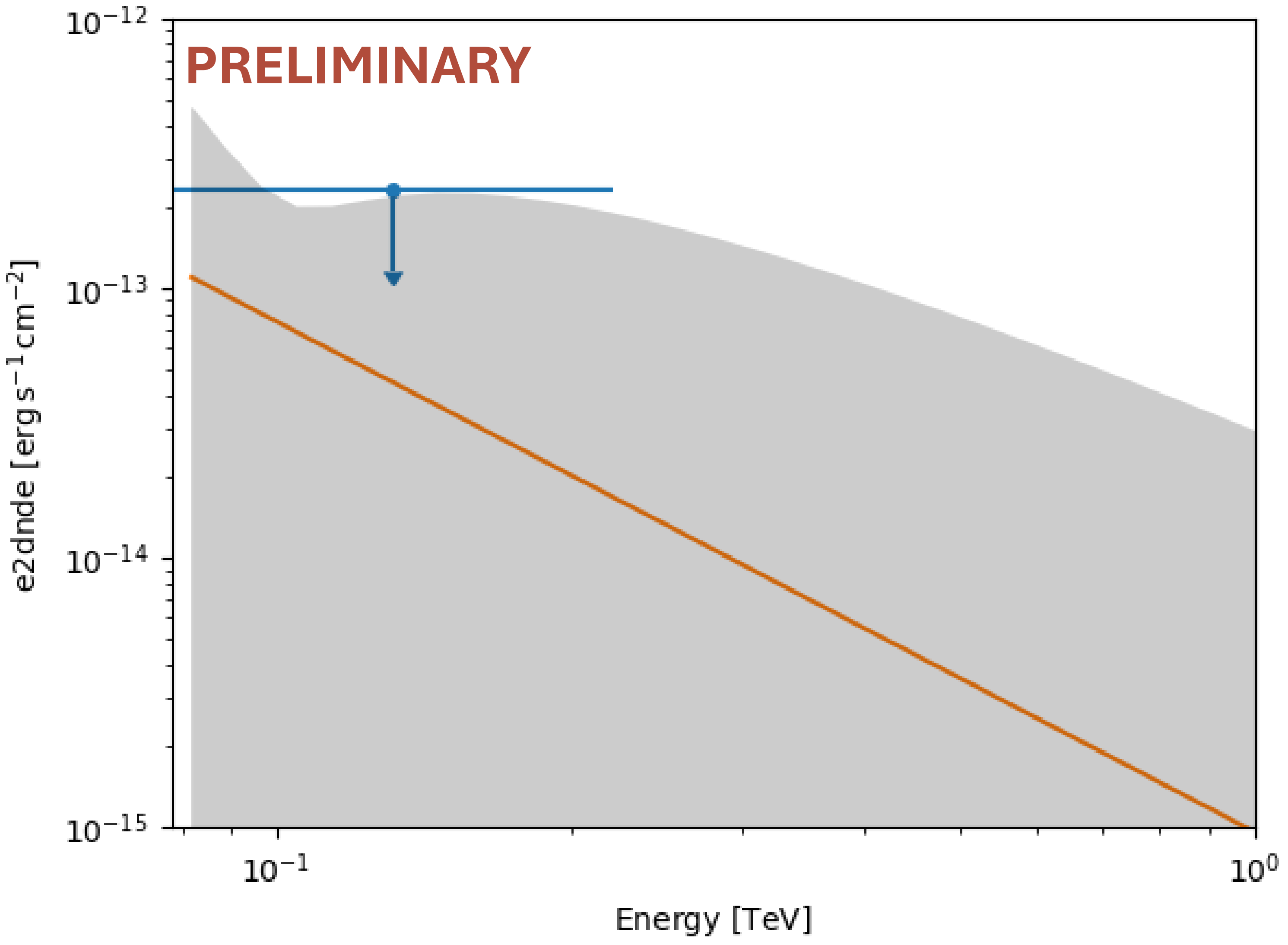


We see a peak significance of 3.7σ with a normal significance distribution, showing no significant gamma-ray emissions

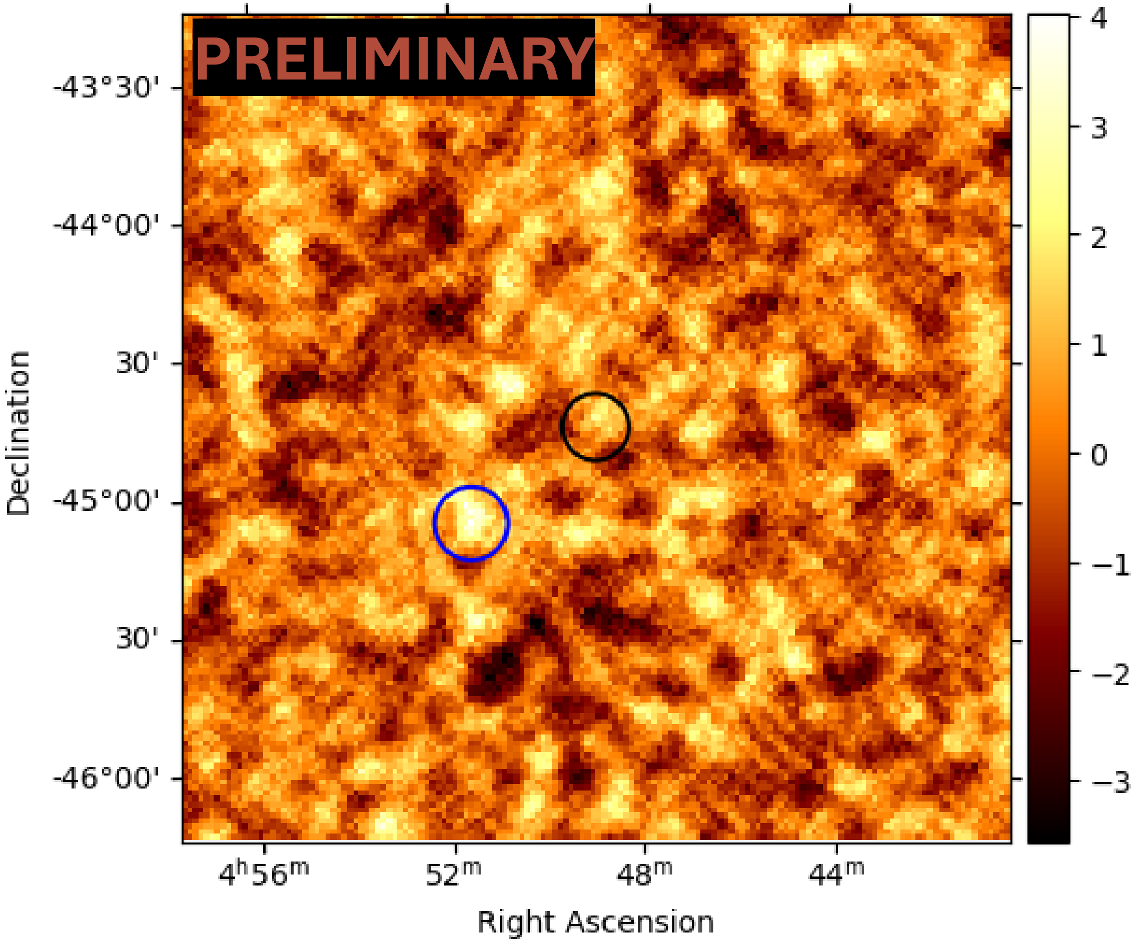
Sagittarius-2 Flux Spectrum

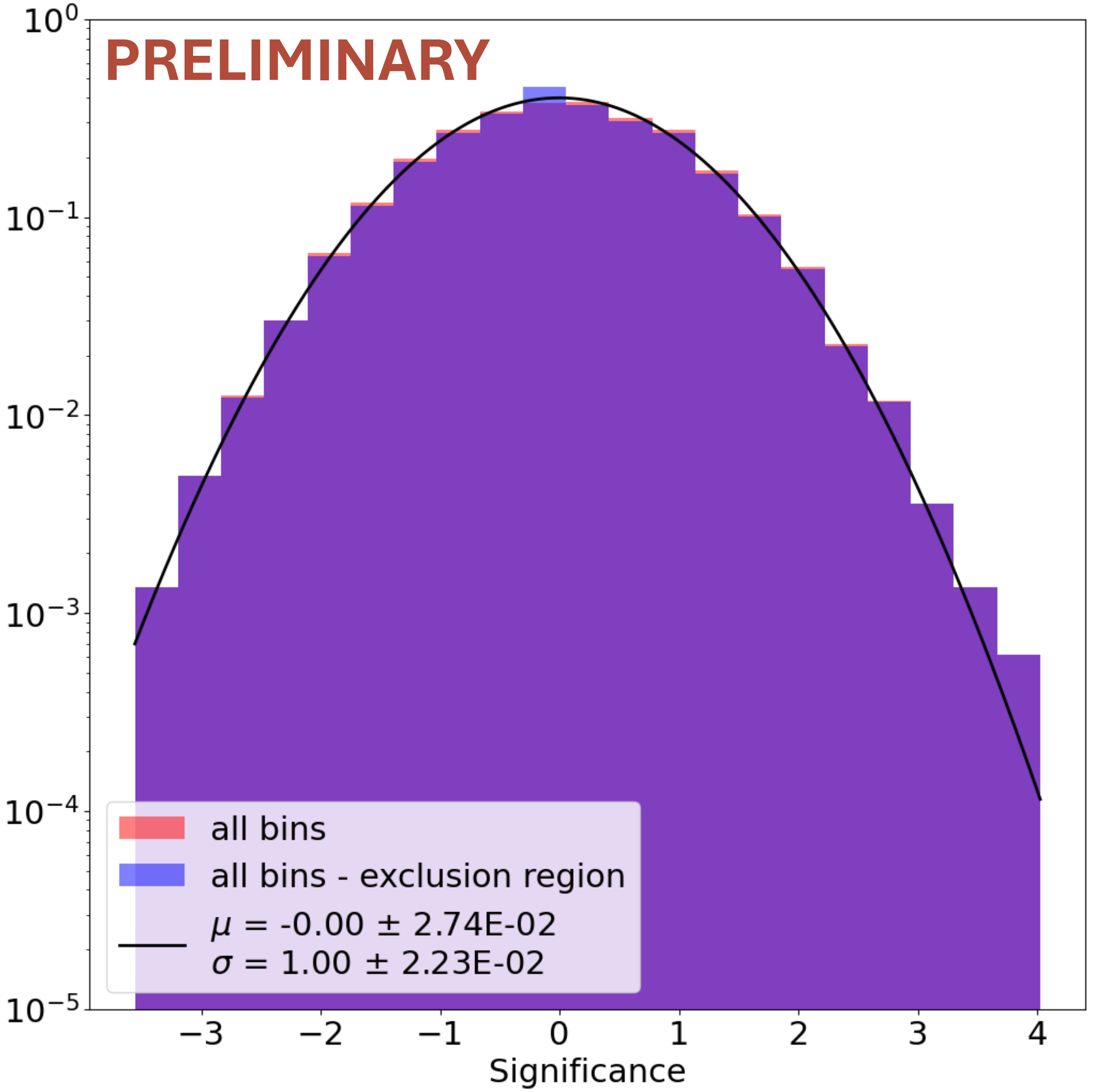
We find the upper limits for 1 energy bin.
For future observations, we can calculate a suggestion for how much more observational time will be needed based on the upper limit

$$S \propto \sqrt{T}$$

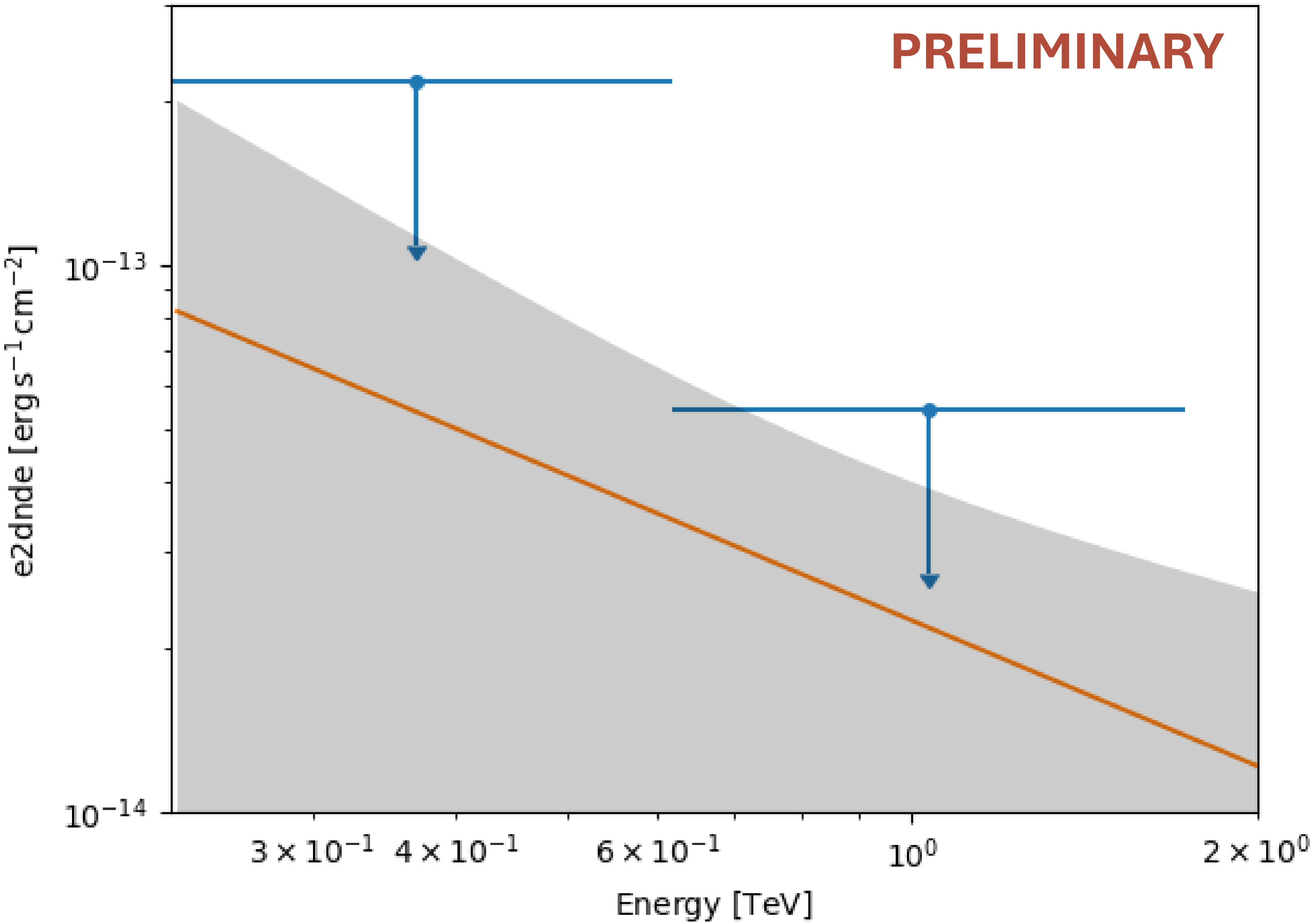


DM Subhalo





We see a peak significance of 4.0σ with a normal significance distribution, showing no significant gamma-ray emissions

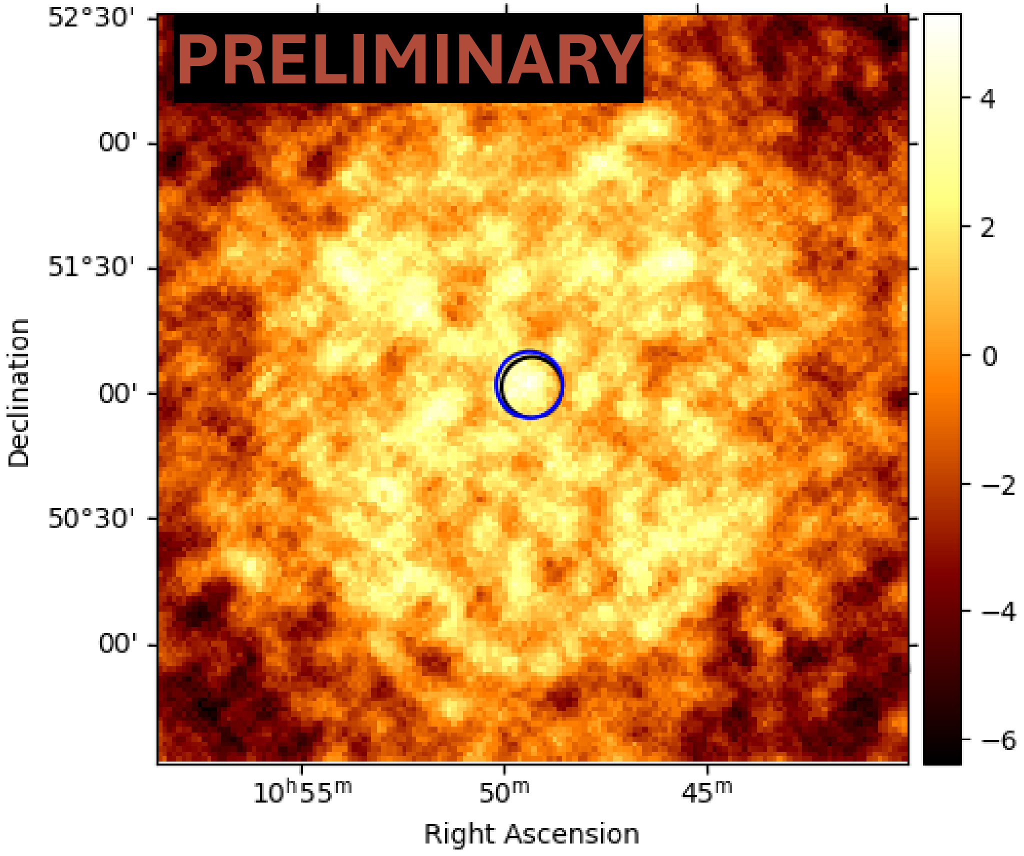


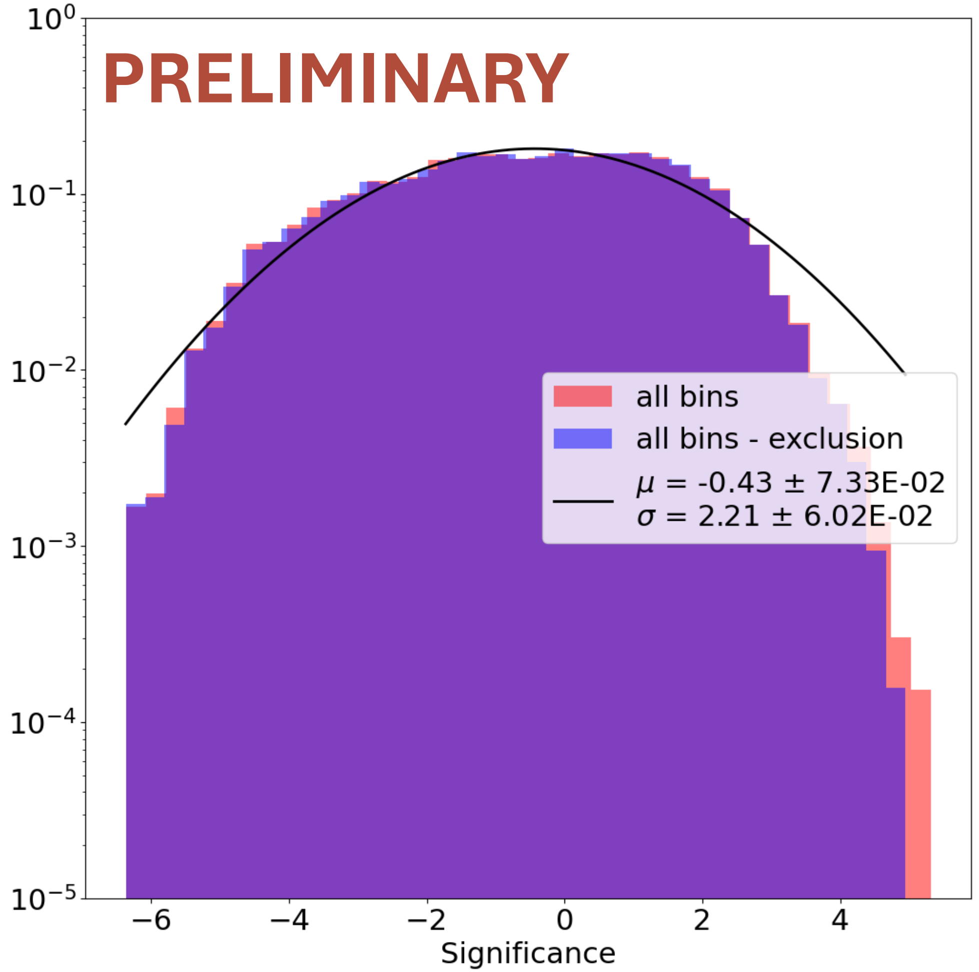
DM Subhalo Flux Spectrum

We find the upper limits for 2 energy bins.
For future observations, we can calculate a suggestion for how much more observational time will be needed based on the upper limits.

Willman-1

A 5.4σ significance detection, with a grain of salt

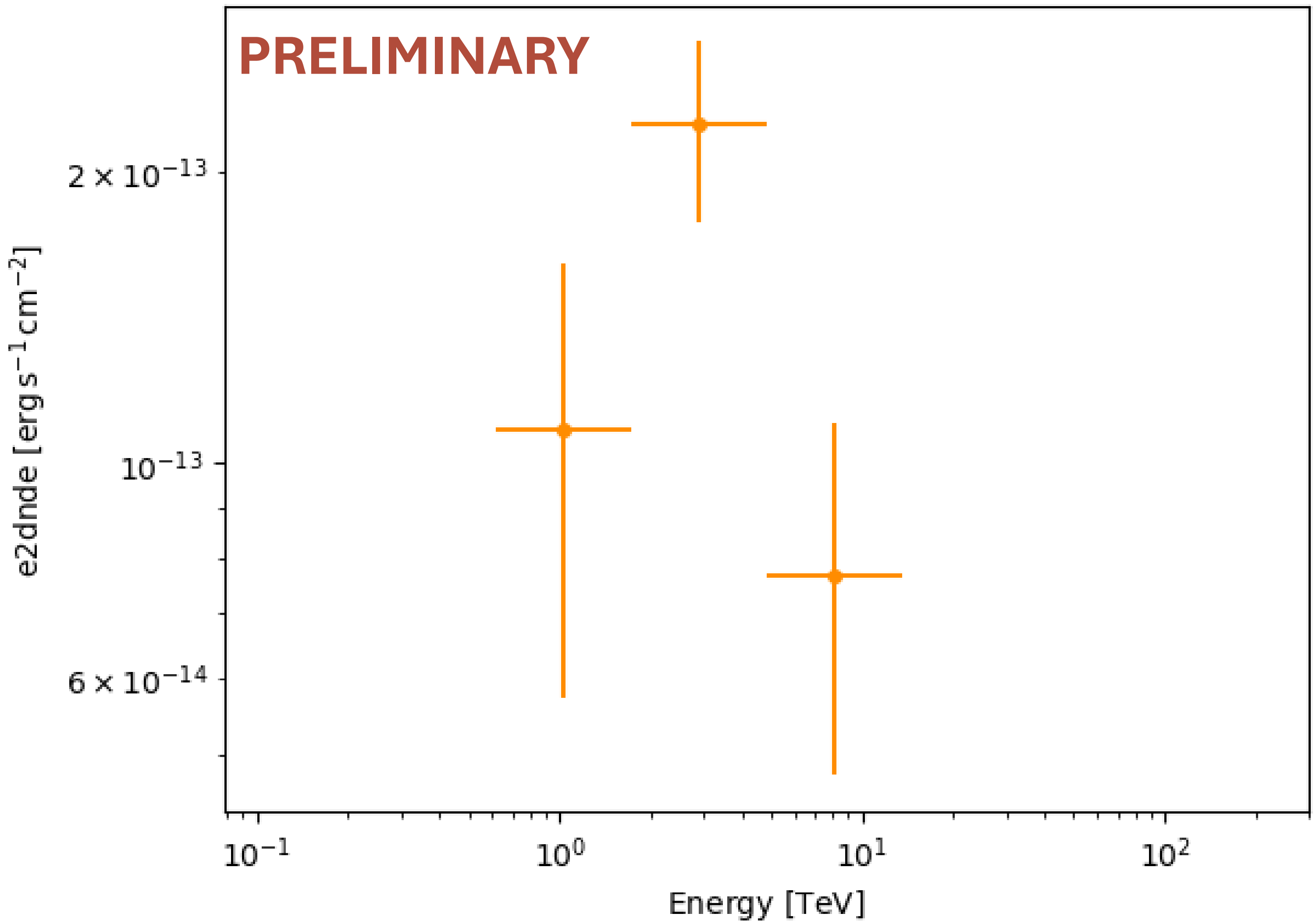




Significance distribution shows either extended source or analytical error.
Analyses of many source sizes provide evidence that the distribution most likely an analytical error.
Further analysis will be required to confirm and fix the error.

Willman-1 Flux Spectrum

Three flux points detected.
More analysis required to verify flux points.



Conclusions

- Dark matter continues to be one of the most compelling mysteries in physics, and indirect DM detection is one convincing avenue forward.
- With CTAO’s unrivaled sensitivity and wide energy range, researchers can analyze VHE-gamma-ray emission better than ever before.
- We pave the way forward by establishing a robust data analysis pipeline
- While results are from simulated data, still useful for comparison, analysis familiarization, and software package verification.

Acknowledgements

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